(12) **UK Patent Application** (19) **GB** (11) **2 309 608** (13) **A**

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(54) **A radiation field analyzer**

(57) The analyzer (10) provides means for analyzing the spatial mode spectrum of radiation received from a scene. In a multimode waveguide embodiment, light from a laser (24) is directed towards a scene through an alumina waveguide structure (12). A portion of the laser light is directed towards a mode generator (28) which selectively converts the laser radiation into one of a series of modes. Laser light returning from the scene is mixed with the light from the mode generator to produce interference signals. These signals are measured by a detector (34) and analysed by a programmed computer (36). By sequentially altering the mode generated by the generator (28) and analysing the resulting signals, a spectrum of the modes returning from the scene is obtained. This spectrum can be used to characterize objects within the scene.
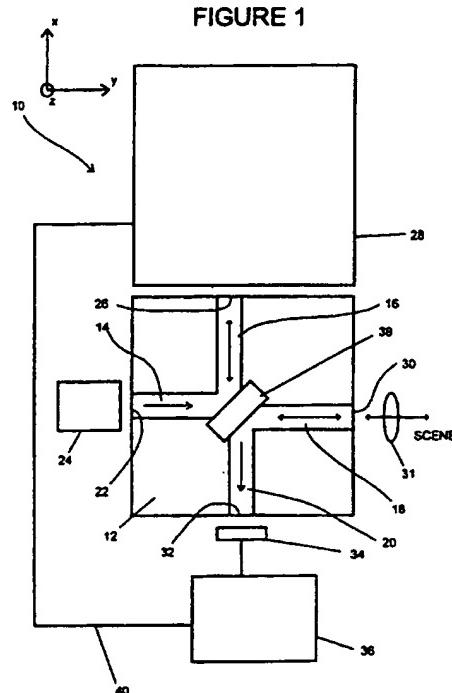
FIGURE 1

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FIGURE 1

FIGURE 2

FIGURE 3

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344

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338

320

328

316

315

312

348

346

340

330

358

352

360

322

314

315

326

318

313

315

334

+y

342

+z

+x
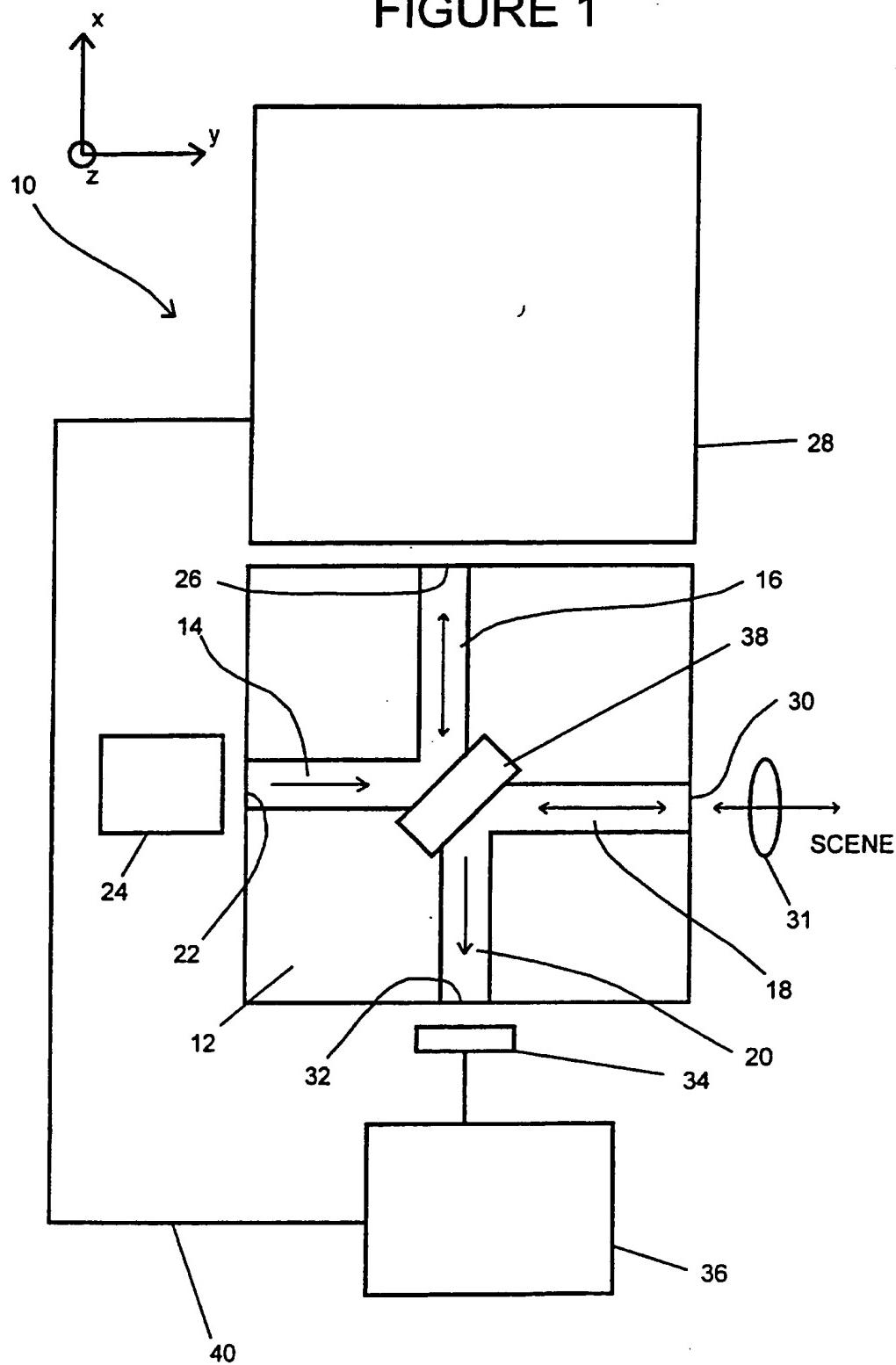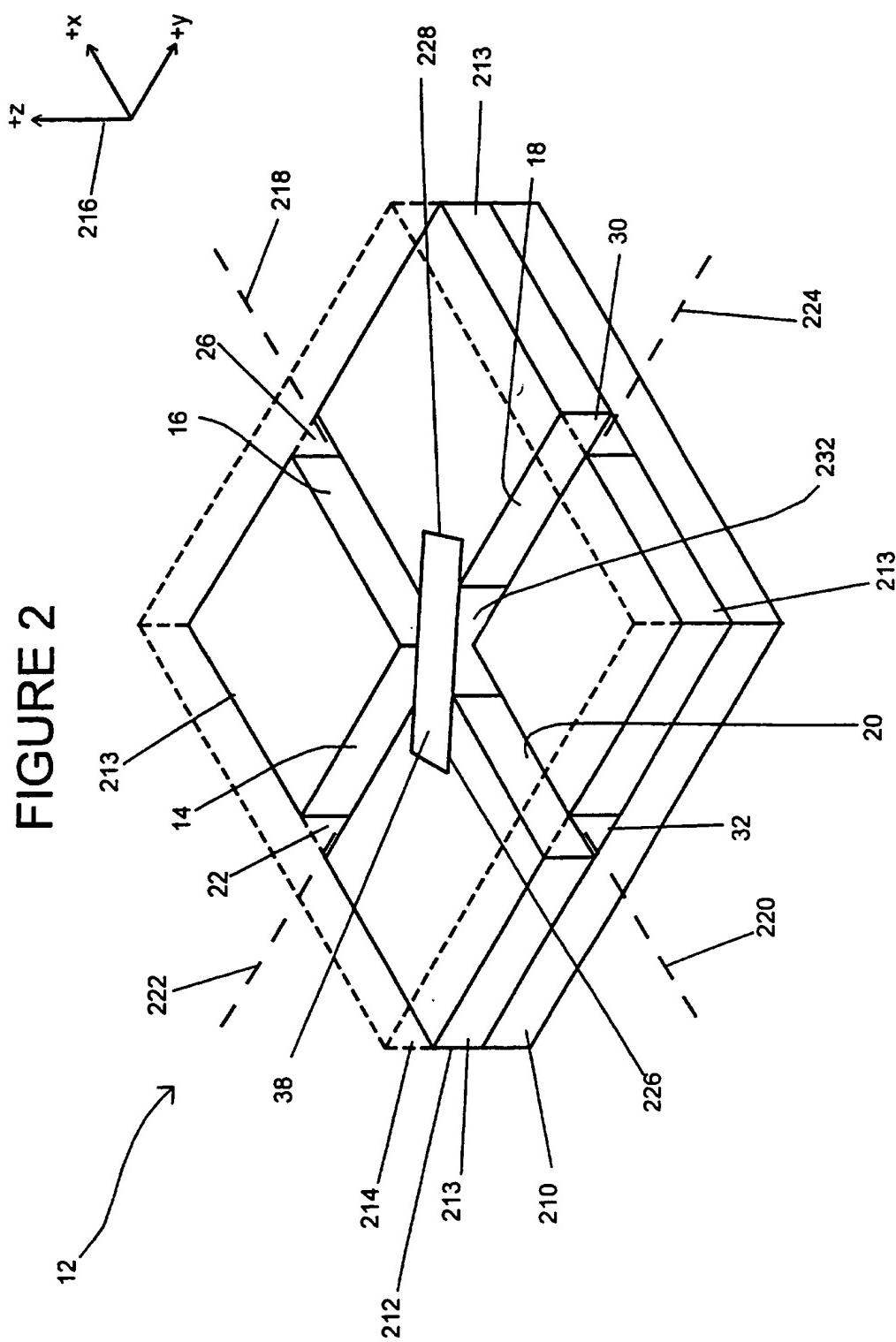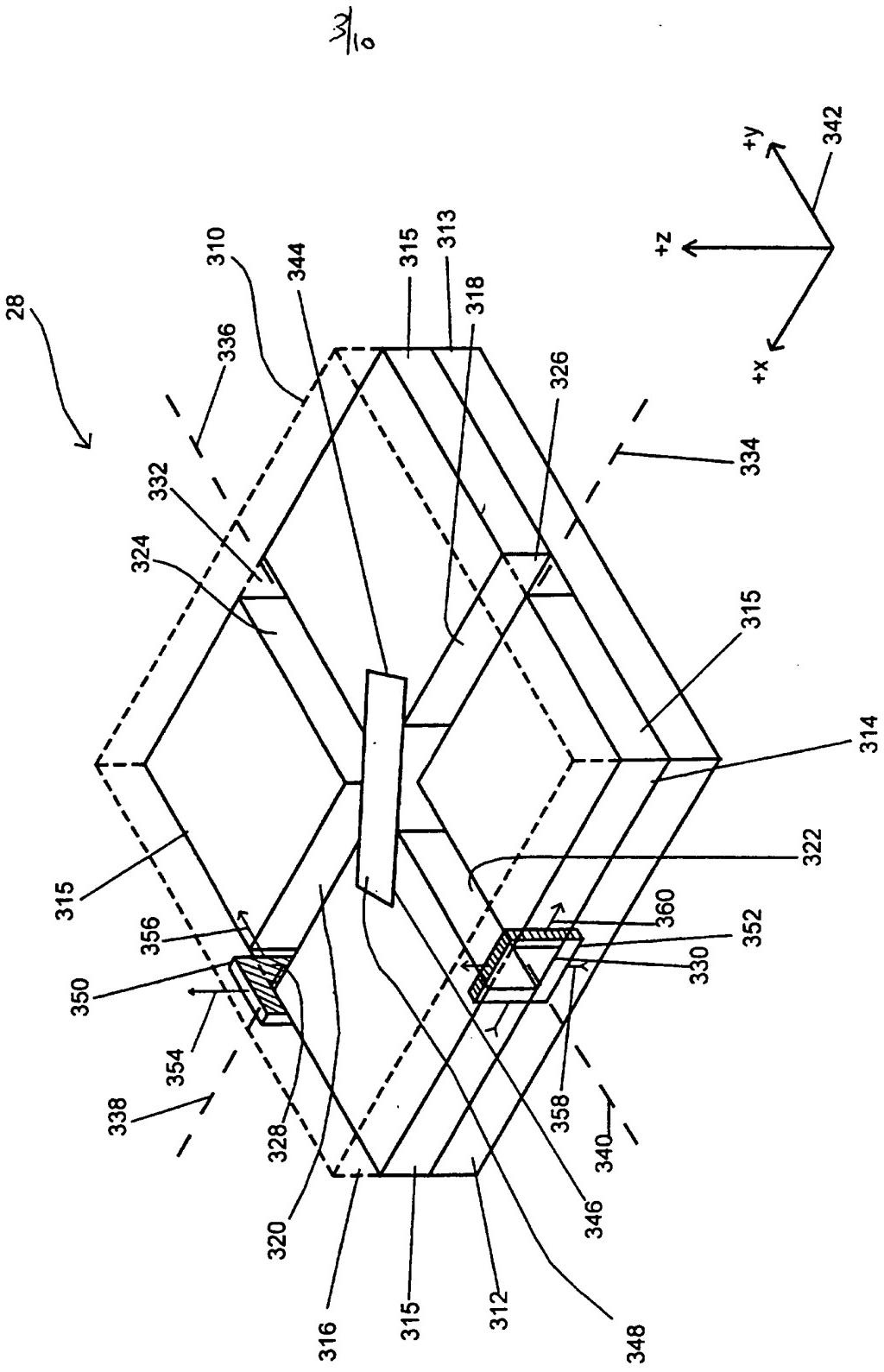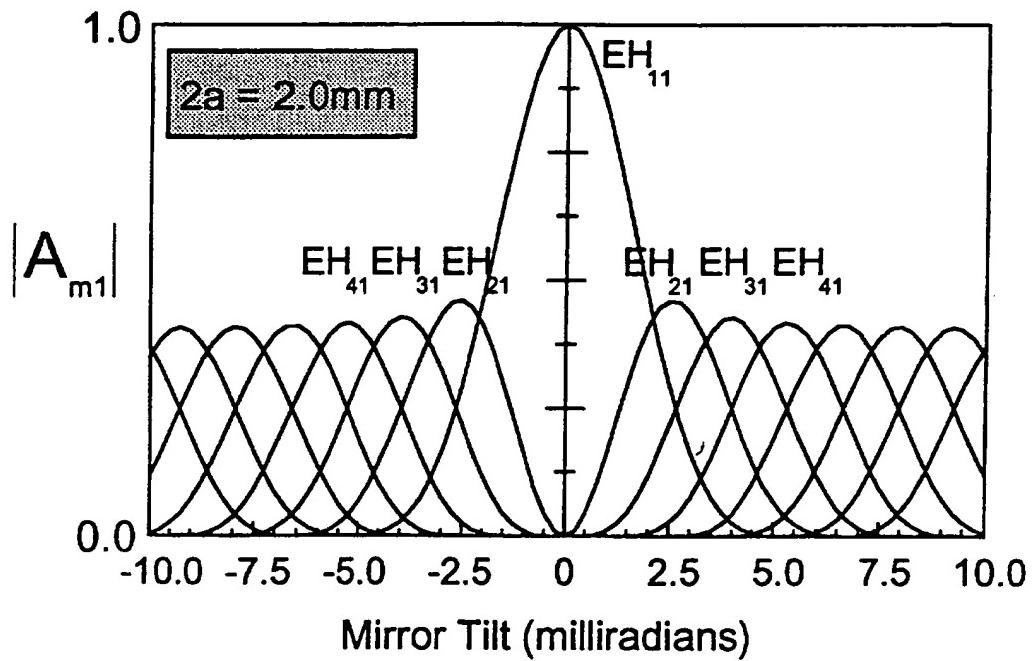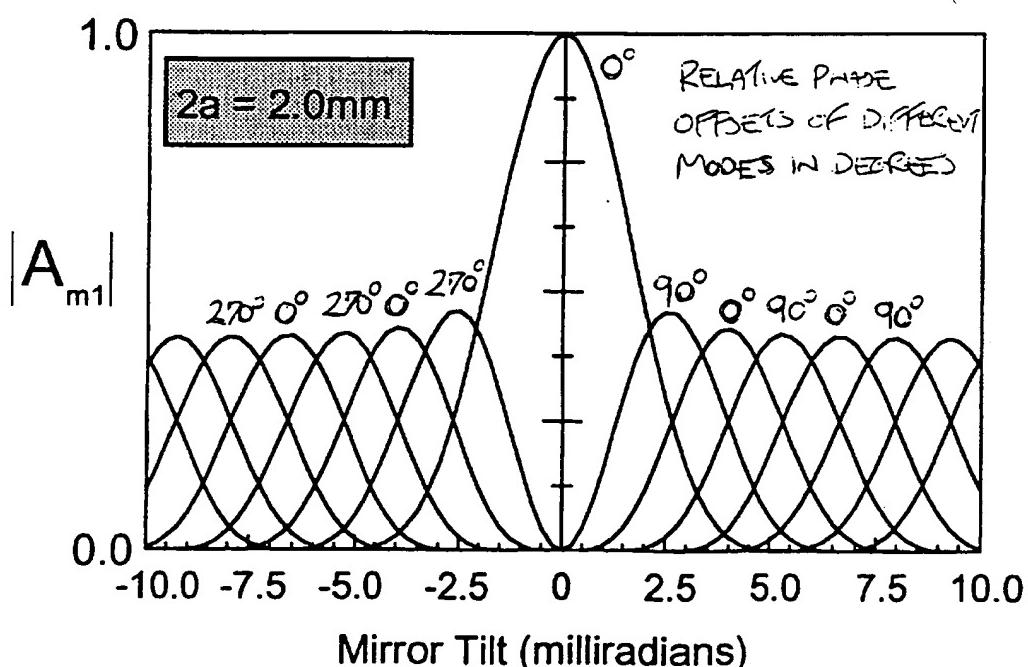
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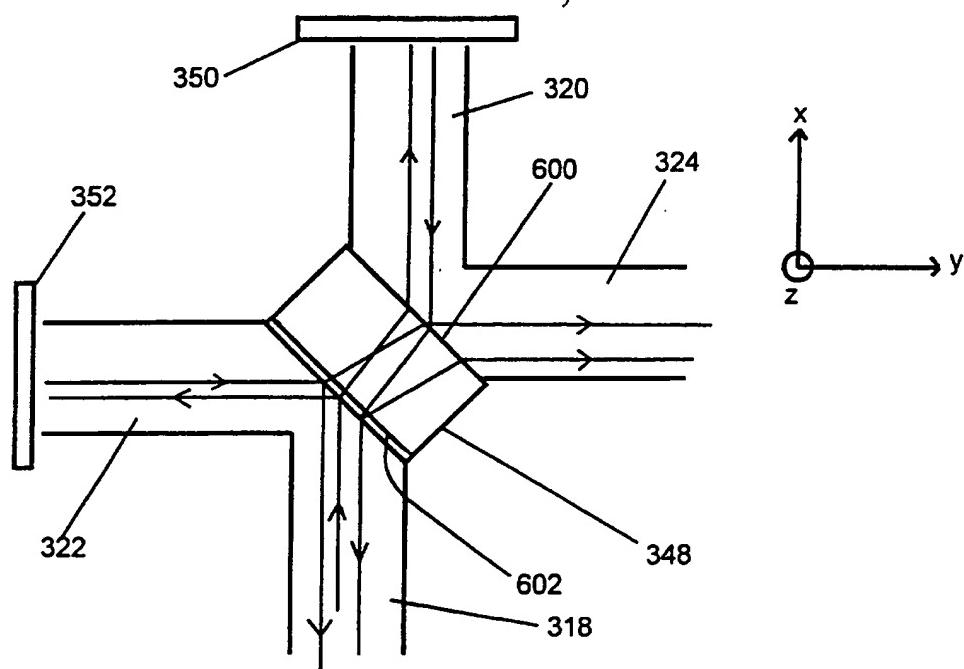
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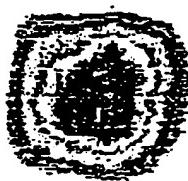
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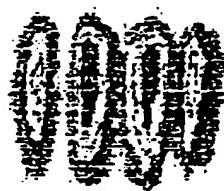
EH₁₁

EH₂₁

EH₃₁

EH₄₁

EH₅₁
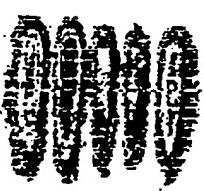
EH₆₁

EH₇₁

EH₈₁

EH₉₁
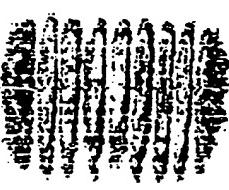
EH₁₀.₁

FIGURE 7.

EH$_{11}$

EH$_{12}$
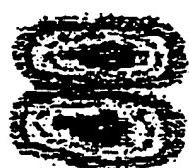
EH$_{13}$
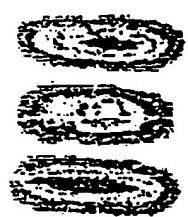
EH$_{14}$
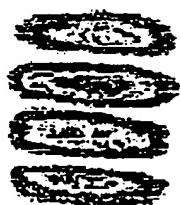
EH$_{15}$

EH$_{16}$

EH$_{17}$
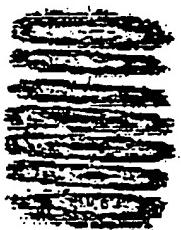
EH$_{18}$
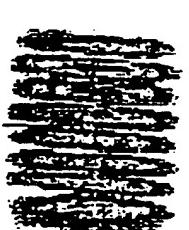
EH$_{19}$
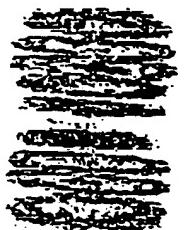
EH$_{1.10}$
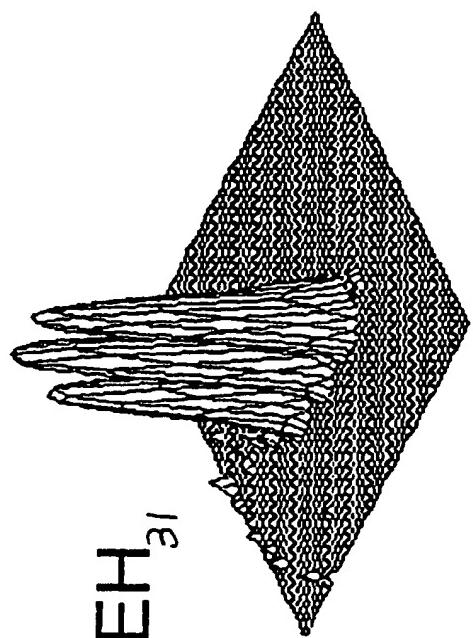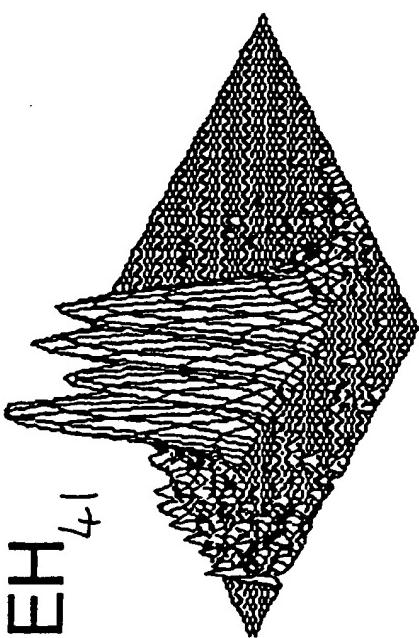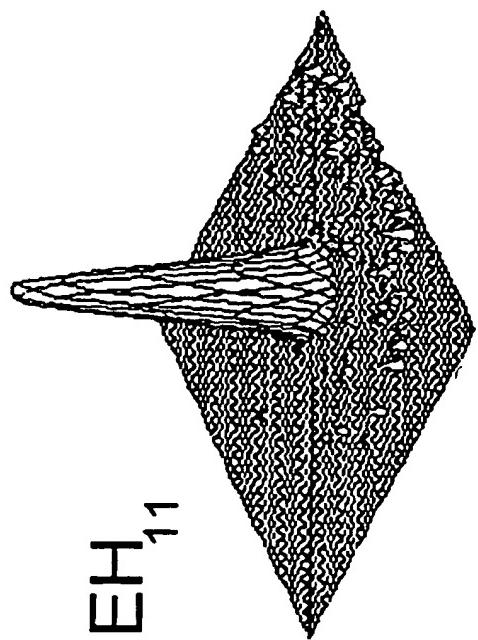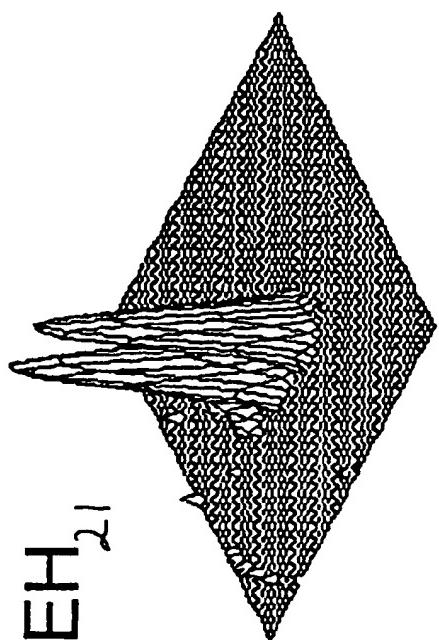
Figure 7c

FIGURE 8

EH$_{11}$

EH$_{21}$

EH$_{31}$

EH$_{41}$

FIGURE 9   9/10

mode converter set to EH₁₁

PREDICTED PEAK-TO-PEAK DETECTOR OUTPUT vs Target Mirror Tilt (mrad.)

FIGURE 9

mode converter set to EH₂₁
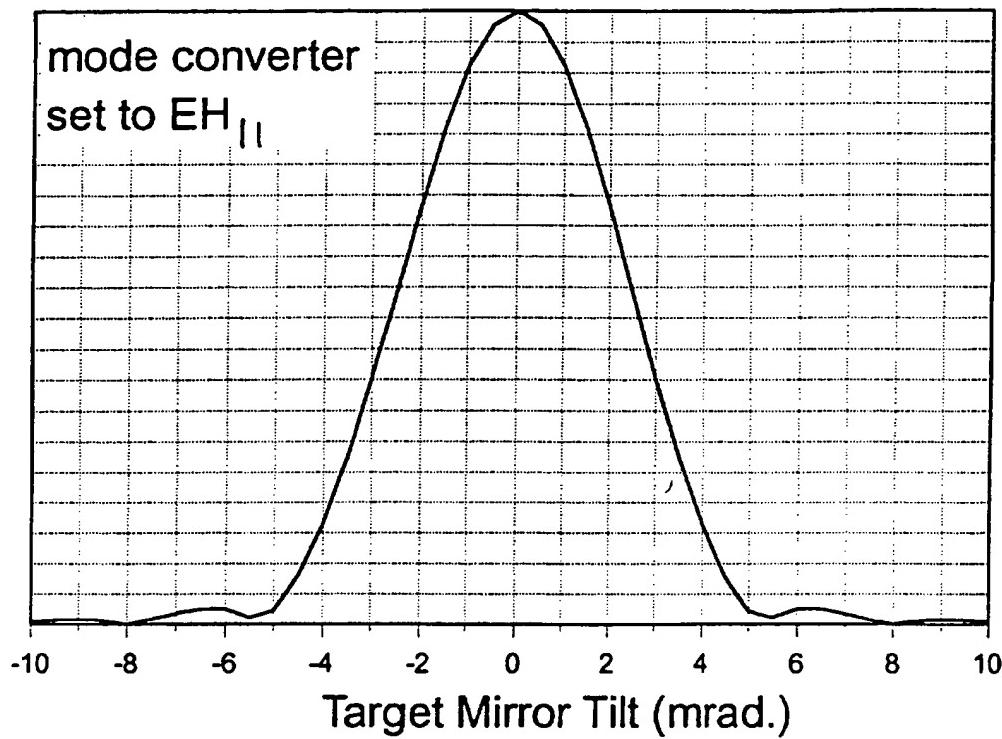
PREDICTED PEAK-TO-PEAK DETECTOR OUTPUT vs Target Mirror Tilt (mrad.)
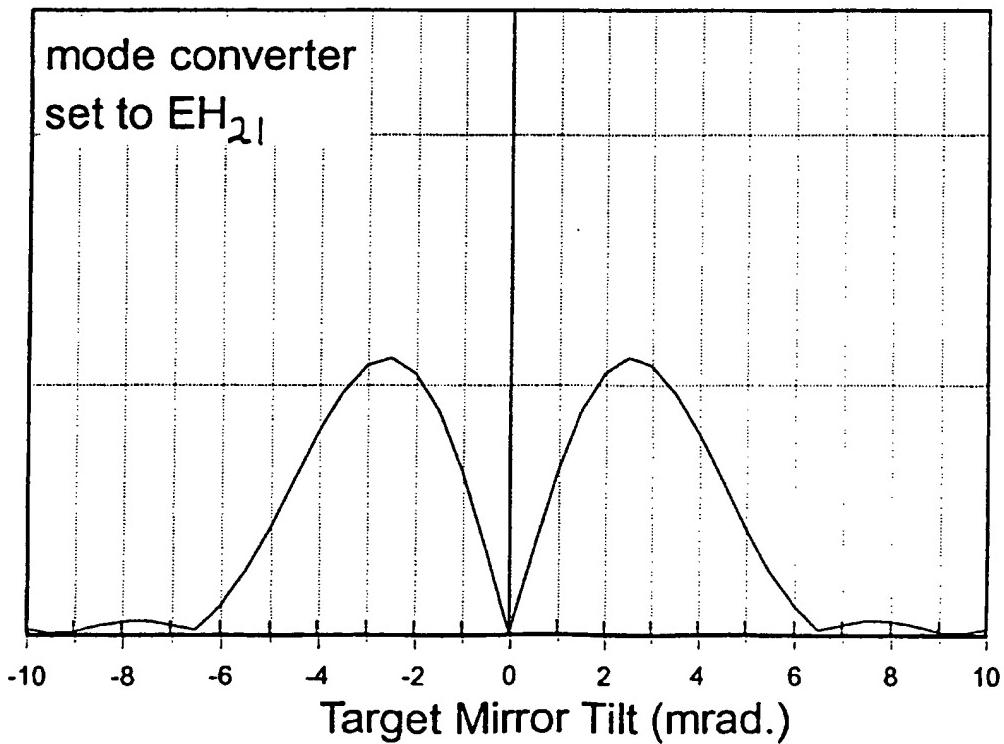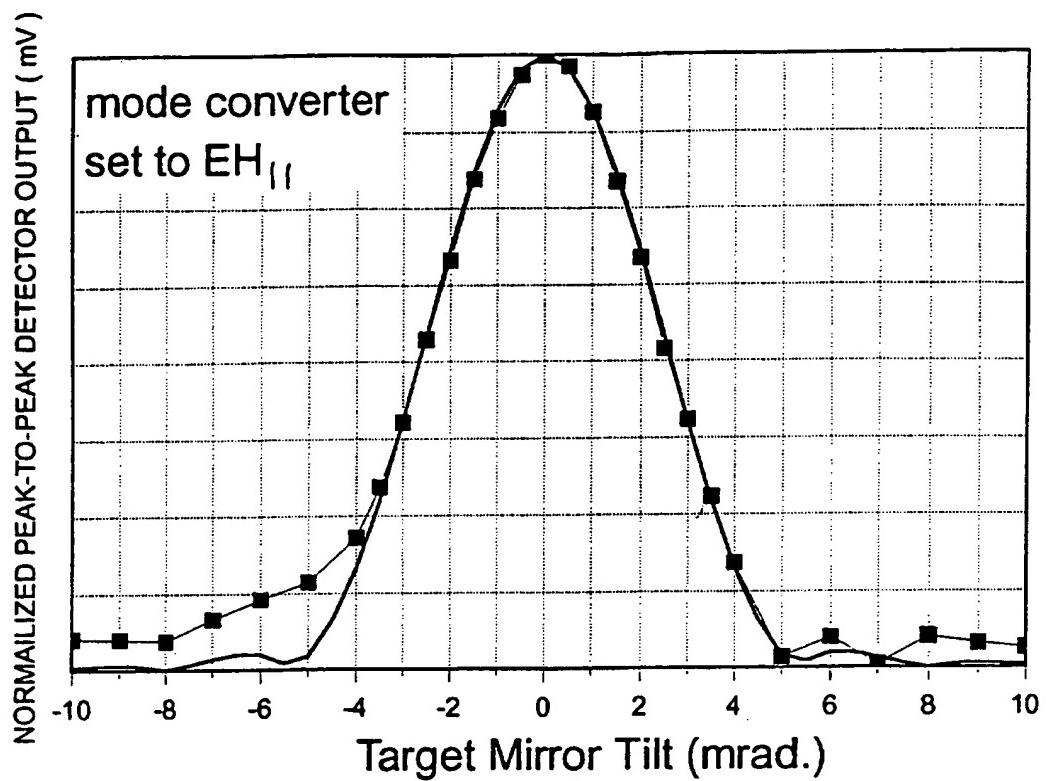
FIGURE 12
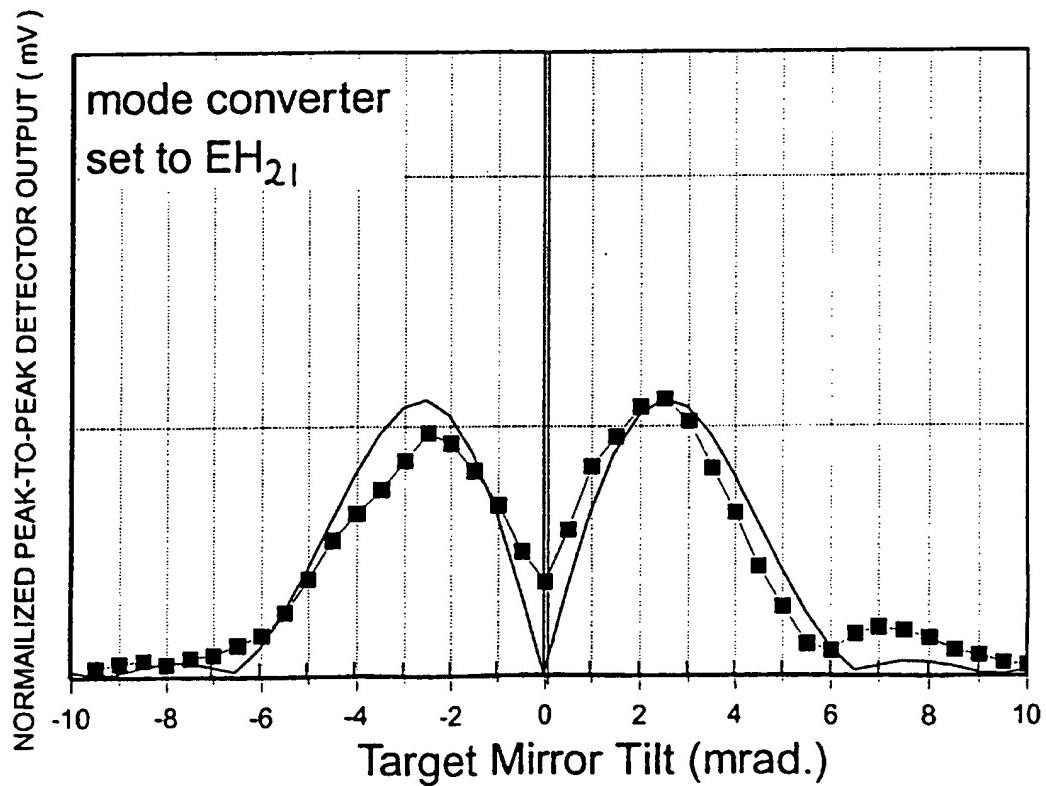
RADIATION FIELD ANALYZER

This invention relates to radiation field analyzers. When a laser source illuminates a scene with coherent radiation the return field contains a significant amount of

5   information about its three dimensional structure and the nature of its surface. The analysis of such fields provides an important basis for target search, tracking and non-cooperative identification procedures. Single aperture single detector heterodyne detection systems with fundamental mode local oscillators are only able to detect the fundamental mode component of the field returned from a scene with the result that a

10   considerable amount of potentially useful information is lost. In the microwave domain this problem is overcome by using an array of sub-apertures. The radiation arriving at each sub-aperture is coherently detected with a separate local oscillator source and detector. In this manner the field across the array is measured in a piece-wise manner. Because of the much shorter wavelength of optical radiation and

15   the different technologies involved, the implementation of sub-aperture receiver array concepts in the analysis of field returns from scenes illuminated with laser radiation has proved difficult in practice.

It is an object of the invention to provide an alternative form of radiation field

20   analyzer.

In particular, the invention provides a radiation field analyzer for analysing at least partially coherent radiation received from a scene wherein the analyzer includes combining means for combining the coherent radiation from the scene with each of a

25   plurality of orthogonal spatial radiation mode fields to provide interference signals, and detecting means for detecting the interference signals and for providing an analysis of the radiation from the scene in the form of a spatial mode spectrum.

In order to generate the interference signals, a degree of coherency must exist

30   between the received radiation and the orthogonal spatial radiation mode signals. The term "scene" is used in a generic sense to include any object in a field of view, including both a ground-scene and individual targets or objects such as aircraft in the sky. The radiation from a scene may be characterised in terms of an orthogonal set of free space modes (e.g. Hermite-Gaussian) or those of a multimode waveguide

(e.g. the hybrid EH_{mn} modes of a square sectioned waveguide where m and n are modal integer numbers greater than or equal to 1). In terms of a waveguide mode analysis the field from the scene, E_{input}, is imaged on the entrance aperture of the waveguide where it excites a spectrum of modes. This process can be expressed as:

5

$$E_{input} = \sum A_{mn} \exp\{i\phi_{mn}\}EH_{mn}.$$

Here A_{mn} and ϕ_{mn} are the modulus and phase of the complex amplitude of the mn^{th} waveguide mode EH_{mn} respectively.

10

For example, for the general case of lossless rectangular waveguides of cross-section 2a×2b the field amplitude of the EH_{mn} mode would have the form:

$$EH_{mn}(x, y, z) = \frac{1}{\sqrt{ab}} \cos[m\pi x/(2a)]\cos[n\pi y/(2b)]\exp(-\beta_{mn} z)$$

15

for m and n odd and:

$$EH_{mn}(x, y, z) = \frac{1}{\sqrt{ab}} \sin[m\pi x/(2a)]\sin[n\pi y/(2b)]\exp(i\beta_{mn} z)$$

for m and n even, where:

20

$$\beta_{mn} = \frac{2\pi}{\lambda_c}\left[1 - \frac{1}{2}\left\{\left(\frac{m\lambda_c}{4a}\right)^2 + \left(\frac{n\lambda_c}{4b}\right)^2\right\}\right]$$

and λ_c is the wavelength of a perfect plane wave in the core of the guide.

By mixing the spectrum of modes excited in the waveguide by the radiation received
25 from a scene with known modes produced by a tunable mode generator, which is also frequency offset from the radiation from the scene, the relative amplitudes and phases of the modes excited by the radiation from the scene in the waveguide can be determined by appropriate measurements of the beat signals produced using a detector.

30

As the modes excited by the radiation from the scene categorise the scene, surveillance and measuring systems based on such a radiation field analyzer can be set to register when certain radiation modes are detected and hence when certain

5   particular targets or objects are present without recourse to a human operator.

Additionally, the transmission of information about a scene becomes simpler than for prior art systems. As a scene is categorised by modes the scene information can be represented by a list of modes present in the scene radiation, together with the

10   amplitudes and phases of those modes.

In a preferred embodiment the scene radiation modes and generated modes are combined in a multimode waveguide structure. Preferably, the generated modes are produced by a generator (or mode converter) which is based on injecting two plane

15   waves (or two waves which approximate two perfect plane waves as closely as possible) at suitable angles and with suitable phases into a multimode waveguide .

Alternatively, the mode generation may be achieved by a laser source providing laser radiation to the multimode waveguide structure. In this case the laser source may be

20   frequency locked and frequency offset from another laser which provides for scene illumination.

The radiation field analyzer may be one of several analyzers in a serial or parallel array. Each analyzer may then be arranged for analysis of a given waveguide mode

25   or series of modes. The analyzers may be fed from one tunable mode converter; alternatively each analyzer in the array may have its own mode generator or mode converter.

Preferentially the radiation field analyzer is provided with a computer system for

30   controlling the modes generated by a tunable mode generator or mode converter and also for analysing the modal spectrum measured by the analyzer.

In order that the invention might be more fully understood, embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings in which:-

5   Figure 1   is a schematic sectional plan view of a radiation field analyzer of the invention;

Figure 2   is a perspective view of a multimode waveguide structure incorporated in the radiation field analyzer of Figure 1;

10

Figure 3   is a perspective view of a tunable mode converter of the Figure 1 analyzer;

Figure 4   illustrates radiation coupling to modes of a rectangular waveguide as a
15   function of radiation input direction;

Figure 5   illustrates relative phase offsets between the modes of Figure 4;

Figure 6   is a schematic view of radiation propagation through a beam splitter of
20   the radiation field analyzer of Figure 1;

Figure 7   is a series of illustrations of waveguide modes produced by the Figure 3 mode converter;

25   Figure 8   shows profiles of radiation modes produced by the Figure 3 mode converter;

Figures 9   show theoretical predictions of the performance of the Figure 1
and 10   radiation field analyzer;

30

Figure 11   is an experimental measurement of the theoretical result illustrated in Figure 9; and

Figure 12   is an experimental measurement of the theoretical result illustrated in
Figure 10.

Referring to Figure 1 there is shown a schematic view of a radiation field analyzer
5   indicated generally by 10. It incorporates a multimode waveguide structure 12 which
has four substantially identical multimode waveguides: a radiation input waveguide
14, a mode conversion waveguide 16, a radiation transmit/receive waveguide 18 and
a detector waveguide 20.

10   The input waveguide 14 has an input aperture 22. A CO_2 laser source 24 is arranged
to direct radiation onto an input aperture 22. Mode conversion waveguide 16 has an
aperture 26. A tunable mode converter 28 is situated at the aperture 26. Mode
converter 28 will be described in more detail later. It is arranged to receive
fundamental mode radiation from conversion waveguide 16 and convert it to radiation
15   of any one of a number of desired modes. With the radiation in the desired mode it is
then transmitted back to the conversion waveguide 16. In addition to converting the
radiation to that of a require mode, a phase modulation or frequency offset of the
radiation is also generated in the mode converter.

20   The transmit/receive waveguide 18 has an aperture 30. Radiation from waveguide
18 is coupled to free space modes outside the multimode waveguide structure 12 via
the aperture 30 and a lens system 31. Also, radiation in free space modes from
external objects is coupled to the transmit/receive waveguide 18 in waveguide modes
via the lens system 31 and the aperture 30.

25

The detector waveguide 20 has an aperture 32. A detector system 34 is arranged to
detect radiation emerging from detector waveguide 20 via aperture 32. Detector
system 34 is connected to a computer system 36 for recordal and analysis of the
radiation emergent from detector waveguide 20.

30

The multimode waveguide structure 12 incorporates a beam splitter 38 situated at
ends of waveguides 14 to 20 opposite to apertures 22, 26, 30 and 32. The
beamsplitter 38 is arranged for substantially equal reflection and transmission of
incident radiation (i.e. it is a 50:50 beamsplitter). It is arranged for reflection of

radiation from input waveguide 14 into conversion waveguide 16 and transmission of radiation from input waveguide 14 into transmit/receive waveguide 18. Similarly, radiation from conversion waveguide 16 is transmitted to detector waveguide 20, and also reflected to input waveguide 14. Also, radiation from transmit/receive waveguide

5   18 is reflected to detector waveguide 20 and also transmitted to input waveguide 14.

The operation of the radiation field analyzer 10 will now be described in general terms, a more detailed theoretical analysis being given later. Fundamental mode radiation from the laser source 24 is arranged to couple to the input waveguide 18 in

10   the EH_{11} mode, i.e. as fundamental mode radiation. The fundamental mode radiation propagates along the input waveguide 14 to the beamsplitter 38. Substantially 50% of the radiation is transmitted through the beamsplitter 38 to the transmit/receive waveguide 18. The remaining substantially 50% of the radiation is reflected to the conversion waveguide 16. The radiation in both waveguides 16 and 18 propagates in

15   the fundamental mode to respective apertures 26 and 30.

The radiation which emerges from aperture 30 couples essentially to the TEM_{00} free-space radiation mode. It illuminates a scene (not shown) and radiation reflected from the scene is coupled into the transmit/receive waveguide 18, via aperture 30. The

20   radiation couples into a number of waveguide modes, of the form EH_{mn}, where m and/or n are greater than or equal to one.

The fundamental mode radiation which emerges from aperture 26 enters the tunable mode converter 28. The converter 28 converts fundamental mode EH_{11} radiation into

25   higher order waveguide modes EH_{mn}. The converter 28 carries out the mode conversion by generating modes in a controlled sequence. The converter 28 is controlled by the computer 36, via a control line 40. The converter 28 generates all modes in the range EH_{11} to EH_{mn}. At any one particular setting, the mode converter only generates a single mode. With m = n = 10 the resolution would be equivalent to

30   a prior art radiation field analyzer having a 10 by 10 array of sub-apertures.

The modes generated by the converter are transmitted to the conversion waveguide 16 via aperture 26. A phase modulator in the mode converter imposes a sinusoidal phase modulation on the generated modes. In one implementation the phase modulator takes the form of a fully reflecting mirror mounted on a piezoelectric stack.

5 The stack is driven by a sinusoidally varying voltage which produces a time dependent axial motion of the mirror of the form $\cos(\omega t)$ where ω is the drive frequency. The amplitude of the drive voltage is arranged so that the limit of the linear motion is $\lambda/2$ where λ is the wavelength of a plane wave in the core of the guide. This motion of the mirror imposed a sinusoidally varying phase shift ($0 \rightarrow$

10 $360°$) on the beam reflected from the mirror.

The phase modulated radiation from the tunable mode converter 28 propagates along the conversion waveguide 16 towards the beamsplitter 38. The radiation from the scene or object which is coupled into the transmit/receive waveguide 18

15 propagates along waveguide 18 towards the beamsplitter 38. The radiation from the converter 28 and the radiation from the scene or object are mixed via the beamsplitter 38 and thence transmitted to the detector 34.

Because of the orthogonality of the waveguide modes the peak-to-peak amplitude of

20 the power variation measured by the detector will only be non-zero when the EH_{mn} mode from the scene or object equates to the EH_{mn} mode generated by the tunable mode converter. For example, when the mode converter 28 generates the EH_{31} mode, there will only be a finite power variation in the transmit/receive waveguide 18 when the radiation from the scene also results in excitation of the mode EH_{31}. The

25 resulting sinusoidal variation in the power is recorded by the computer 36 and used to deduce the modulus and phase of the EH_{31} component in the field from the scene. Consequently, from knowledge of the mode settings and the relative amplitudes and phases of the modes generated by the tunable mode converter 28 and of the sinusoidal power measurements made by the detector 34, the complex amplitudes of

30 all the EH_{mn} radiation modes present in the radiation received from the scene can be determined.

This enables the radiation field from a scene to be characterised according to the EH_{mn} modes excited in the transmit/receive waveguide. The higher the order of modes used in the analysis, the greater the resolution by which the scene radiation field can be characterised. Lower order modes may provide information on the bulk

5 characteristics of the scene; for instance the presence of EH_{21} mode. with two intensity peaks, indicates the presence of two main vertical components in the scene. Conversely, higher order modes such as the mode $EH_{10,10}$ provide information about smaller scale detail of the scene. Consequently, scene radiation fields can be characterised in terms of the EH_{mn} modes which it excites. Scene radiation fields

10 may be calibrated; i.e. a known object field may be characterised in terms of the EH_{mn} modes which it produces, and the analyzer 10 may then be arranged to register when the EH_{mn} modes corresponding to that object are received by the detector 34. The analyzer 10 may then be used as the basis of a surveillance system in which objects to be detected by the analyzer 10 are initially calibrated in terms of the EH_{mn}

15 modes which they excite.

Figure 2 is a perspective view of the multimode waveguide structure 12 of Figure 1. The multimode waveguide structure 12 is fabricated from alumina. It is composed of three layers: a substrate layer 210 forming the lower walls of the hollow waveguides,

20 a waveguide layer 212 comprising an arrangement of tiles 213 forming the vertical walls of the hollow waveguides, and a top layer 214 indicated by dotted lines and forming the upper walls of the hollow waveguides.

The waveguide layer 212 defines the shape of the input waveguide 14, the mode

25 conversion waveguide 16, the radiation transmit/receive waveguide 18 and the detector waveguide 20 shown in Figure 1. Each of the resulting hollow waveguides 14 to 20 is of constant square cross-section of side 2a where a is equal to one millimetre.

30 The dispositions of the waveguides 14 to 20 will now be described with reference to axes 216. The mode conversion waveguide 16 and detector waveguide 20 have respective central longitudinal axes 218 and 220 extending in the x-direction. Axis 220 is offset from axis 218 by 0.93 mm in the positive y-direction. Similarly, input waveguide 14 and transmit/receive waveguide 18 have central longitudinal axes 222

and 224 respectively extending in the y-direction. Axis 222 is offset from axis 224 a
by 0.93 mm in the positive x-direction.

The waveguide layer 212 also has two slots 226 and 228. These are situated
5   respectively between waveguides 14 and 20, and waveguides 16 and 18. The
beamsplitter 38 is situated in slots 226 and 228 at a common intersection 232 of the
waveguides 14 to 20. The beamsplitter is fabricated from zinc selenide and has a
thickness of 1.9 mm. A multidielectric coating is evaporated onto its surface allowing
50% of the incident light to be transmitted and 50% reflected.
10

The waveguides 14 to 20 have respective apertures 22, 26, 30 and 32 at the end of
the waveguide layer 212. The laser source 24 is centrally located on longitudinal axis
222. Tunable mode converter 28 is centrally located on axis 218, 1.0 millimetre
distant from aperture 26 of conversion waveguide 16. The detector 34 is a cooled
15   4.0 mm square chip of cadmium mercury telluride (CMT) which is located centrally on
axis 220; it is positioned so as to capture all of the radiation emitted from the aperture
32.

Figure 3 shows a perspective view of the tunable mode converter 28 of Figure 1. It
20   incorporates a multimode waveguide structure 310 comprising four hollow
waveguides. The structure 310 comprises three layers 312, 314 and 316. Layer 312
consists of a substrate plate 313 which forms the lower walls of the hollow
waveguides, layer 314 comprises an arrangement of tiles 315 which form the vertical
walls of the hollow waveguides and layer 316, indicated by dashed lines, is a top
25   plate 317 which forms the upper walls of the hollow waveguides.

The arrangement of tiles 315 forms four multimode waveguides 318, 320, 322 and
324. Waveguide 318 is an input waveguide; waveguide 320 is a first mode
conversion waveguide; waveguide 322 is a second mode conversion waveguide; and
30   waveguide 324 is a mode checking waveguide. Each waveguide is of square cross-
section of side 2.0 mm. Each waveguide 318 to 324 has a respective aperture 326,
328, 330 and 332 at the corresponding edge of the layer 314.
The waveguides 318 to 324 have corresponding central longitudinal axes 334, 338,
340 and 336. Axis 338 is offset from axis 334 by 0.93 mm in the positive y-direction,

as indicated by axes 342. Similarly, axis 336 is offset from axis 340 by 0.93 mm in the positive x-direction. In operation, axis 334 is parallel and coaxial with the axis 218 of Figure 2.

5   The layer 314 has two slots 344 and 346, extending throughout its thickness. Slot 334 is situated at the intersection of waveguides 318 and 324; and slot 346 at the intersection of waveguides 320 and 322. The slots 334 and 346 each support a zinc selenide beamsplitter 348, of thickness 1.96 mm.

10   The first and second mode conversion waveguides 320 and 322 have respective associated mode conversion mirrors 350 and 352. These are located centrally along axis 336 and 338, and a distance of approximately 1.0 mm away from apertures 328 and 330. The mirrors 350 and 352 are mounted on respective motorised mounts (not shown). The mounts enable the mirrors 350 and 352 to be rotated about selected

15   axes. Mirror 350 is rotatable about central axes 354 and 356, which are respectively a vertical axis parallel to the z-direction, and a horizontal axis parallel to the y-direction. Mirror 352 is rotatable about central axes 358 and 360, which are respectively parallel to the z-direction and to the x-direction. Additionally, the separation between mirrors 350 and 352 and their associated waveguide apertures

20   328 and 330 can be varied by linear motors on the mounts. Movement of the mirrors is controlled by computer 36 of Figure 1.

The mode converter 28 is located adjacent to the multimode waveguide structure 12 such that light from aperture 26 couples into aperture 326 of input waveguide 318 of

25   the converter 28.

The operation of the mode converter 28 will now be described. Fundamental mode radiation entering aperture 326 propagates along input waveguide 318 to beamsplitter 348. As beamsplitter 348 is a 50:50 beamsplitter, essentially half the

30   incident radiation is transmitted through it to the first mode conversion waveguide 320. The substantial part of the remainder is reflected into the second mode conversion waveguide 322. The radiation propagates along waveguides 320 and 322, and emerges from apertures 328 and 330. The radiation is incident on mirrors 350 and 352, and reflected back towards the apertures 328 and 330.

The coupling of the reflected radiation from mirrors 350 and 352 into waveguides 320 and 322 is dependent on the angles of tilt of the mirrors 350 and 352. Figure 4 shows a graph of the variation of magnitude of the moduli of the modes coupled into the waveguide 320 after reflection from mirror 350. The same graph applies for radiation coupled from mirror 352 to waveguide 322. It can be seen that the moduli of the waveguide modes coupled into the waveguides varies with tilt angle of the respective mirror. Positive tilts relate to clockwise rotations of the mirrors 350 and 352 about respective vertical axes (i.e. z-axes) 358 and 360. Negative tilts refer to anticlockwise rotations. The graph of Figure 4 is for EH_{mn} modes where n is equal to 1.

From the graph it can be seen that at zero tilt then only EH_{11} radiation mode is coupled to the respective waveguides. However, at increasing positive tilts the modulus of the EH_{11} mode decreases until it becomes substantially zero at 11.0 milliradians tilt. Conversely, the modulus of, the EH_{21} mode increases rapidly at positive tilts, to a maximum of about 2.5 milliradians tilt. The maximum amplitude of the modulus of the mode EH_{21} does not, however, reach a value equivalent to that of the EH_{11} mode; rather it is restricted to about two-thirds of that value.

At higher positive tilts the other higher order modes: EH_{31}, EH_{41}, EH_{51} etc., also begin to be coupled to the respective waveguides. These modes have maximum amplitudes at about 4.0, 5.5 and 7.0 milliradians of mirror tilt respectively. Their maxima are substantially the same as that of EH_{21} mode. For negative mirror tilts the moduli of all modes are the same as for positive tilts, however their phases are different. The mirror tilt required to maximize the amplitude of any given mode, except EH_{11} (for which the maxima is achieved with zero tilt), can be predicted to a good approximation by the formula: $\theta = m\lambda_c/8a$, where, 'θ' is the tilt in radians, 'm' is the mode number of the $EH_{m1}{}^{th}$ mode, 'λ_c' is the wavelength of a plane wave in the core of the guide (in the case of hollow waveguides, the wavelength of a plane wave in free space), and a is the half width of the waveguide. For example, if m = 3, λ = 10.6 μm, and a = 1.0 mm, then θ = 0.003975 radians, i.e. approximately 4 milliradians in good agreement with the numerical predictions of Figure 4.

Whilst Figure 4 highlights how the moduli of the excited modes varies as a function of mirror tilt Figure 5 illustrates how, in addition, the phase offsets between the modes are also a function of mirror tilt. It can be seen that for positive mirror tilts the antisymmetric modes EH_{21} and EH_{41} are offset by 90° (or $\pi/2$) from the symmetric modes EH_{11}, EH_{31} and EH_{51}. Conversely, for negative mirror tilts the antisymmetric modes are offset by 270° ($3\pi/2$).

From Figure 4 and 5 it can be seen that for any particular mirror tilt angle a multiplicity of modes are coupled to the respective waveguide. For example, for a positive tilt of 4 milliradians there are contributions from modes EH_{11}, EH_{21}, EH_{31}, EH_{41} and EH_{51}. However, the magnitudes of the moduli of the modes are different. The modulus of the fundamental mode is about 0.05, as is that of EH_{51}, the moduli of modes EH_{21} and EH_{41} is approximately 0.25, whilst the modulus of EH_{41} is at a maximized at a value of 0.4.

For the analysis of radiation from a scene by the technique outlined, it is desirable that the mode converter 28 should generate substantially single EH_{mn} modes at any one time. If it generates multiple modes then these may beat with multiple modes from the scene radiation field to be analyzed, causing multiple beat signals. More sophisticated signal processing techniques would then be required in order to determine which modes were present in the radiation detected by detector 34. If single modes could be generated by the mode converter the analysis could be much simpler.

With the aim of generating essentially pure modes, the symmetric and antisymmetric modes may be separated so that approximately only one mode is produced from the mode converter 28 at any one time for any given mirror tilt. The modes are separated by virtue of the coherent mixing process at the beamsplitter 348.

Figure 6 shows a schematic view of the propagation of radiation through the beamsplitter. The beamsplitter 348 has two faces 600 and 602. Face 600 has an anti-reflection coating whilst face 602 has a multidielectric coating providing 50% transmission and 50% reflection. Consequently radiation propagating towards the

beamsplitter 348 is transmitted through and reflected from the face 602 to waveguides 320 and 322 respectively in equal ratios. The reflection actually occurs at the interface of the high refractive index beamsplitter 348 and low refractive index air adjacent to it. For radiation approaching this interface from mirror 352 the radiation is travelling in a low refractive index medium and is reflected at the air interface with the high refractive index medium of the beamsplitter 348. The radiation undergoing this reflection does not undergo a phase change. Conversely, the radiation approaching the interface from the mirror 350 is travelling in the high index medium of the beam splitter and is reflected from the interface with the lower refractive index medium - i.e. the air surrounding the beamsplitter 348. The radiation undergoing this reflection undergoes a π radian, or one hundred and eighty degree phase shift.

Following the coupling of radiation into waveguides 320 and 322, reflection from the mirrors 350 and 352 once again results in radiation being reflected from, and transmitted through, the point 604. Consequently the radiation from the mirrors 350 and 352 can be combined at point 604 and can couple modes into both of the waveguides 318 or 324. For the intensity of a given EH_{mn} mode to be maximized in output waveguide 318 the phase difference between radiation from mirrors 350 and 352, via waveguides 320 and 322 and the at the interface 604, must satisfy the following:-

$$\phi_{mn350} - \phi_{mn352} = p2\pi,$$

where p is an integer, ϕ_{mn350} is the phase of the EH_{mn} mode injected into waveguide 318 from mirror 350, and ϕ_{mn352} is the phase of the same mode injected into waveguide 318 from mirror 352.

In order to achieve this situation for any given mode the mirror 350 is arranged for lateral movement in the x-direction (axial movement along the guide axis) over a distance x. This movement produces a phase change ϕ_c in ϕ_{mn350}, given by:

5
$$\phi_c = 2x \cdot \frac{2\pi}{\lambda_{mn}},$$

where λ_{mn} is the wavelength of the EH_{mn} mode. As the laser source 24 is a CO_2 laser, the wavelength of the free space radiation is 10.6 μm. To obtain a phase change ϕ_c would require a movement $x = \lambda_{mn}\phi_c/4\pi$. In practice, in order that like

10 modes are in phase, ϕ_c would be adjusted so that $(\phi_{mn352} - \phi_{mn350})$ would be an integral multiple of 2π radians.

From Figure 5, it can be seen that for positive tilts of mirror 350 about the z-axis (see Figure 3) the antisymmetric modes EH_{21}, EH_{41}, EH_{61} etc., are offset by 90° from the

15 symmetric modes, whilst for negative tilts of the mirror 350 about the z-axis the antisymmetric modes EH_{21}, EH_{41}, EH_{61} etc., are offset by 270° from the symmetric modes. Considering the situation where mirror 350 has a positive tilt, and mirror 352 has a positive tilt (which following reflection from the beamsplitter 348 equates to an effective negative tilt in output guide 318 as far as the relative phases of the modes

20 are concerned), if by the application of an appropriate phase shift, applied via the piezo-electrically controlled displacement of mirror 350 it is arranged that the symmetric modes transmitted by the beamsplitter 348, from mirror 350 into output guide 318, are in phase with the symmetric modes reflected by the beamsplitter 348, from mirror 352 into output guide 318; then these symmetric modes will constructively

25 interfere at point 604, and produced a beam of symmetric modes which will be coupled into waveguide 318. Conversely with the same mirror tilts the transmitted and reflected antisymmetric modes from mirrors 350 and 352 will be out of phase at point 604 and will destructively interfere in the outgoing field of waveguide 318. Simultaneously, these antisymmetric modes will be in phase in the outgoing field of

30 waveguide 324 and will interfere constructively, whilst the symmetric modes in outgoing field of waveguide 324 will be out of phase and will interfere destructively.

Conversely, where the mirror 350 is displaced so as to achieve destructive interference between the symmetric modes in the outgoing field in waveguide 318 the antisymmetric modes will be in phase and will interfere constructively. Simultaneously in waveguide 324 the outgoing symmetric modes will interfere
5   constructively and the antisymmetric modes will be absent.

In the above situation the mode set which is coupled to waveguide 324 may be used as a check on the modes which are produced in the output field of waveguide 318 i.e. the output from the mode converter 28. For example, if antisymmetric modes are to
10   be output via waveguide 318 then waveguide 324 must contain symmetric modes, and vice versa. The waveguide 324 may have a detector array (not shown) opposite its output aperture 322 for the purpose of analysing the modes.

The previous argument demonstrates how the output radiation from the mode
15   converter 28 can be selected to be either a symmetric or an antisymmetric mode and how the purity of a given mode can be maximized by choosing the tilt magnitudes on the mirrors 350 and 352 according to the expression $\theta = m\lambda_c/8a$. However, unless the input to the mode converter is a perfect plane wave the output at each of these settings may contain multiple modes and so there will be a further requirement to
20   suppress the effects of unwanted modes. This is achieved as follows.

From the graph of Figure 4 it can be seen that for zero mirror tilt then the only mode generated in the fundamental mode EH_{11}. At 4.0 milliradians of mirror tilt the EH_{31} is the dominant mode produced, but there are also small contributions from EH_{51} and
25   EH_{11} modes. Antisymmetric modes are being ignored here, as these can be eliminated as previously described. By measuring the output of the analyzer with the mode converter 28 set with zero tilt of mirrors 350 and 352 then the amplitude of the fundamental mode EH_{11} can be directly ascertained, as that is the only mode generated at zero tilt.
30

The amplitude of the EH_{31} mode can be determined by measuring the output from the analyzer with the mirrors in the mode converter set to tilts of +2.5 milliradians. From Figure 4 the contribution of the EH_{31} and EH_{11} modes are substantially the same and all other symmetric modes have very low magnitudes. The amplitude of the EH_{11}

mode at 2.5 milliradians of mirror tilt can be determined from the previous measurement at zero tilt. From the graph of Figure 4 the amplitude of the EH_{11} mode varies with mirror tilt in a known manner, and the amplitude at any tilt can then be found from the amplitude at zero tilt. As the EH_{11} amplitude at 2.5 milliradians is

5   known the contribution to the EH_{31} mode signal can be deduced. Similarly, at 5.5 milliradians of mirror tilt the amplitude of the EH_{51} mode can be determined, from knowledge of the previously determined EH_{11} and EH_{31} modes and of the output of the analyzer with the mirrors in the mode converter 28 set to this mirror tilt.

10   Similarly, from Figure 4, when the antisymmetric modes are selected by appropriate setting of the PZT the amplitude of the EH_{21} mode can be found by measuring the output from the analyzer when the mirrors in the mode converter are set at +1.5 milliradians of tilt. Here, the mode converter output is mostly due to the EH_{21} mode, with EH_{41} having only a small contribution. At +4.0 milliradians the contributions from

15   EH_{21} and EH_{41} are the same with the amplitudes of all other antisymmetric modes being extremely small. By measuring the output from the analyzer in this situation and compensating for the contribution of the EH_{21} mode the amplitude (i.e. modulus) of the EH_{41} mode can be deduced.

20   From the foregoing it can be seen that the scene radiation field received by the analyzer can be characterised in terms of the individual modes present, by arranging for only symmetric or antisymmetric modes to be produced and by a knowledge of the modes generated at various tilt angles or mirrors 350 and 352.

25   The foregoing has been concerned with the generation of EH_{m1} modes. This is achieved by tilting mirrors 350 and 352 about their vertical axes and in the same sense. The EH_{1n} modes can be generated by rotating mirrors 350 and 352 about their horizontal (y or x) axes and in the same direction (the requirement for the rotations to be of the same sense arise from the fact that the reflection from the beam

30   splitter inverts the image). The resultant mode graphs are substantially identical to those of Figures 4 and 5, but with the "n" numbers varying whilst the "m" number is fixed at 1.

Higher order modes with both m and n greater than 1 can also be generated by the mode converter 28. This can be achieved simultaneously titling the mirrors 350 and

352 about both their horizontal and vertical axes. The EH_{mn}^{th} mode is obtained by tilting the mirrors 350 and 352 to the required tilt about the vertical axis for the mth mode, as was done in relation to Figure 4, and about the horizontal axis for the appropriate tilt for n^{th} mode. For these higher order modes, the mirrors 350 and 352

5   must be tilted about their horizontal axes with opposite senses, whilst the tilts about their vertical axes should have the same sense.

Figures 7a and 7b are illustrations of the mode outputs produced by the mode converter 28 at differing settings. Figure 7a shows the radiation intensity patterns

10   output from waveguide 316 when the mode converter 28 was set to produce modes EH_{11} up to $EH_{10,1}$. For example, the EH_{41} intensity pattern has a horizontal row of four intensity peaks. Figure 7b shows the radiation patterns output from the waveguide 316 when the mode converter 28 was set to produce modes EH_{11} up to $EH_{1,10}$. As an example, the EH_{17} pattern has a vertical column of seven intensity

15   peaks. The fundamental mode EH_{11} consists of a single central intensity peak. In general, intermediate mode patterns have various combinations of columns and rows of intensity peaks. The EH_{mn}^{th} mode has m×n intensity peaks.

Figure 8 shows quasi three dimensional profiles of four of the modes produced by the

20   mode converter 28, the modes being EH_{11}, EH_{21}, EH_{31}, and EH_{41}. It can be seen that these modes have respectively, one, two, three and four, intensity peaks.

The radiation from the mode converter 28 couples into the conversion waveguide 16 via aperture 26. The multimode radiation from the scene couples into the

25   transmit/receive waveguide 18 via aperture 30. The radiation in the respective conversion waveguide 16 and transmit/receive waveguide 18 propagates towards the 50:50 beamsplitter 38.

The radiation from the scene is composed of a linear combination of EH_{pq} modes with respective complex amplitude $A_{pq} \exp (i\phi_{pq})$. The EH_{pq} modes are produced by an input optical field, E_{input}, coupling to the waveguide 18 at aperture 26. Consequently, E_{input} can be represented by the E_{pq} modes as

5

$$E_{input} = \sum A_{pq} \exp\left(i\,\phi_{pq}\right)EH_{pq}$$

Essentially, the waveguide 18 carries out a Fourier analysis of the optical field E_{input} at its entrance aperture 26. The complex amplitudes are then the coefficients of the

10   Fourier series and the modes excited in the waveguide 18 are a modal representation of the field from the scene.

The radiation modes in waveguides 16 and 18 are now mixed together at the beamsplitter 38. By moving the mirrors 350 and 352 of the mode converter

15   simultaneously through a sinusoidally varying displacement of maximum amplitude, Y, for each EH_{rs} setting of the mode converter a beat signal is produced on the detector. A displacement of at least 2.65 μm, brought about by the application of a sinusoidally varying voltage being applied to the piezo-electric transducers, is necessary in order to ensure that the phase of the EH_{rs} mode from the converter

20   changes by π radians.

The coherent beating of an EH_{rs} mode from the converter and the mode spectrum from the scene results in a beat field which is propagated along the detector waveguide 20. It emerges from aperture 32 and is detected at detector 34. Under

25   these conditions, the time varying 2D intensity profile produced on the detector 34 is given by:

$$I_b (x, y, t) = \left[\frac{A_{pq}}{\sqrt{2}}EH_{pq}\right]^2 + \left[\frac{A_{rs}}{\sqrt{2}}EH_{rs}\right]^2 + \frac{A_{pq}}{\sqrt{2}}EH_{pq}\frac{A_{rs}}{\sqrt{2}}EH_{rs}\cos(\omega t + \rho)$$

30   Here A_{pq} and A_{rs} are the moduli of the complex amplitudes of the modes in the scene field and those produced by the mode generator, respectively, and ρ is the difference of their arguments, $(\rho_{pq} - \rho_{rs})$, i.e. their phase difference. By integrating over the

waveguide cross-section the time variable component of the power falling onto a detector which captures all the radiation emanating from the guide, is given as:

$$P_b = 2 \frac{A_{pq}}{\sqrt{2}} \frac{A_{rs}}{\sqrt{2}} \cos(\omega t + \rho) \int_{-a}^{+a} \int_{-b}^{+b} EH_{pq}(x, y) \; EH_{rs}(x, y) \, dx \, dy$$

5

and the peak-to-peak value of P_b as:

$$P_{b_{pk-pk}} = 4 \frac{A_{pq}}{\sqrt{2}} \frac{A_{rs}}{\sqrt{2}} \int_{-a}^{+a} \int_{-b}^{+b} EH_{pq}(x, y) \; EH_{rs}(x, y) \, dx \, dy$$

10 Because of the orthogonal nature of the waveguide modes the integral term and hence the peak-to-peak amplitude of P_b will only be non-zero when the modes are of the same order, i.e. p = r and q = s, simultaneously. Under this condition the value of the peak-to-peak amplitude of P_b coupled with a knowledge of the magnitude of A_{rs}, allows direct evaluation of, A_{pq}, the modulus of the complex amplitude of the mode

15 EH_{pq}. Furthermore, by making comparative measurements of the relative phase offsets between the sinusoidal variation of P_b and the piezo-electric modulator drive signal, for different mode settings of the mode tunable local oscillator, the relative phase differences between the modes can also be established. In this manner the complex amplitude of each mode in the input field can be measured hence the

20 complete form of the field can be deduced.

In practice the accurate measurement of the relative phases of the modes in the input field is based on two important assumptions.

25   (i)   That the waveguide optical path length between the entrance aperture of the waveguide (into which the field which is to be analyzed is imaged) and the detector is equal to the waveguide optical path length between the output from the mode converter and the detector. If this were not the case, corrections would have to be made to the measurements based on the mode dispersion equation.

30

        (ii)   That the individual modes produced at the output plane of the mode

converter all have the same relative phase. If this were not the case the relative phase offsets would have to be established in an initial set-up procedure. This could be based on the injection of a known input field, e.g. the EH_{11} field returned from a tilted mirror. The values of the phase offsets deduced in this manner could either be

5   used to correct the measured data in the computational phase of the field analysis process. Alternatively the phase offset data could be used to establish zero phase offsets between the generated modes by applying suitable d.c. offset voltage levels to the phase modulator in the mode converter for each mode generated. This process is analogous to the "phase up" procedure which has to be undertaken in phased

10   array receivers in order to ensure that the phases of the local oscillator signals applied to the mixing points behind each subaperture are the same.

The analyzer 10 may be calibrated before use by locating a target mirror (not shown) at the aperture 30 of transmit/receive waveguide 18. The mirror can be tilted to

15   generate the modes analogous to those of Figure 4. Consequently the relative phases of the modes propagating in waveguide 18 can be deduced from the output of detector 34, by beating the EH_{mn} modes from the converter 28 with the modes generated by the target mirror. The amplitude and phase of the modes generated by the converter 28 are known, and the amplitude of modes generated by the target

20   mirror are also known. This enables the relative mode phases to be deduced.

A calibration procedure which would take account of phase offsets between the modes generated by the mode converter is now considered in more detail. With reference to Figure 1 consider the situation where a target mirror placed at the

25   aperture 30 is tilted by -4.0 mrad about the z-axis. From Figure 4 it is known that this results in excitation of modes EH_{11}, EH_{21}, EH_{31}, EH_{41}, and EH_{51}. The mode converter is tuned to EH_{11} and the phase difference, χ_1, between a sample of the drive signal applied to the phase modulator in the mode converter and the output from the detector is measured. In practice this could be done with an oscilloscope.

30   The mode converter is then tuned to provide the mode EH_2· and the phase difference measurement is repeated. The result this time is a value χ_2. From Figure 5 it is known that $\chi_2 - \chi_1$ should equal $270°$, the correction to χ_2 is defined as χ_{2c}, and evaluate it such that $\chi_2 + \chi_{2c} - \chi_1 = 270°$. The value of χ_{2c} is recorded. In an analogous manner the phase corrections for the other modes excited by this value of

tilt magnitude are evaluated. The target mirror is now tilted by -9.0 mrad, this results in excitation of modes EH_{51}, EH_{61}, EH_{71}, EH_{81} and EH_{91}. This value of tilt was chosen to include EH_{51} which occurred in the first data set. Measurements of the relative phase offsets with respect to EH_{11} from the initial set of measurements which

5   included EH_{11} and EH_{51}. The strategy of overlapping the sets of modes for which measurements are made is important because in moving from one value of mirror tilt to another, unless the axis of rotation runs exactly through the waveguide axis, which is unlikely in practice, an axial shift of the mirror surface is also effected which introduces and additional unknown phase shift.

10

Tilts of the target mirror about the orthogonal x-axis and compound tilts about both the horizontal and vertical axes allow access to a large mode spectrum. In this context, as described earlier, the value of mirror tilt required to excite a given set of modes is to a good approximation given by, $\theta = n\lambda/8a$, where, n is the number related

15   to the mode at the centre of the set and, a, is the half width of the waveguide. For example if it is desirable for EH_{31} to be the centre of the set then n = 3, and with λ = 10.6 μm and a = 1.0 mm, this gives θ = 4 mrad as used earlier. If it is desirable for mode EH_{33} to be at the centre of the set excited, the mirror would be tilted by 4.0 mrad about both the x and z axes. With a computer controlled mirror mount and

20   suitable interface electronics the whole set-up process could be automated.

If it were desirable to analyze the tilted input field at any value of tilt magnitude illustrated in Figure 4 then a mode tunable local oscillator would be needed which would at least produce modes EH_{11} to EH_{51}. It would then be necessary to make

25   moduli and phase measurements for each of the five modes in turn. Because of the unique nature of the input field it is interesting to note that any point in the range the maximum number of modes simultaneously excited is, five. Images of real objects are likely to result in much more complex mode spectra in terms of both the numbers

and orders of the modes excited. The resolution with which such images could be analyzed will depend on a number of factors, these include:

(i)   the highest order mode accessible with the mode tunable local oscillator,

(ii)   the purity of the modes it produces, and

(iii)   the accuracy with which the modal amplitude and phase measurements can be made. With temporally varying fields another important factor will be the time taken for the measurement to be made. This will depend on the number of modes the analysis is made with and the time taken for each measurement. The latter will itself depend on how quickly the peak-to-peak value of P_b can be evaluated and this in turn will be a function of the phase modulation frequency. Signal to noise issues are also likely to effect overall measurement resolution and time.

Because the approach to field analysis described is reliant on performing sequential measurements on each of the modes that the local oscillator can be tuned through, although potentially very fast, it is inherently slower than a phased array which in principle is real time. However, the mode analysis approach has significant technological advantages over the phased array in that it only requires a single aperture and a single detector to form a very sophisticated coherent field measuring system. As such it might well be possible to upgrade existing single aperture, single detector systems, with the addition of a mode tunable local oscillator. Additionally, the fact that the complex mode amplitude outputs from the system provide a direct Fourier transform of the object field, could have significant advantages as far as image processing, pattern recognition and data storage are concerned. In the context of increasing the speed of measurements it is possible to conceive systems where several local oscillators running on different modes are used to make simultaneous measurements of the different spatial components of a field. In relation to phased array systems the modal analysis approach might also be used to provide improved resolution behind each sub-aperture. Hybrid systems based on a

combination of phased array and modal analysis techniques might lead to new approaches to coherent receiver design.

Figures 9 and 10 show predictions of the way in which the peak-to-peak amplitude of

5   the beat signal received by the detector 34 would vary if the scene was itself a mirror placed at the exit of waveguide 18 and was tilted from -10 mrad to +10 mrad. Figure 9 relates to the case where the mode converter was set to produce the fundamental EH_{11} mode, whilst in Figure 10 the mode converter is set to generate the mode EH_{12}. It can be seen that signal maxima are recorded at the target mirror tilt angles which

10   maximize the coupling to the mode which the mode converter is tuned to. Figures 11 and 12 illustrate comparisons of the theoretical predictions illustrated in Figures 9 and 10 with experimentally generated results for the case where the mode converter is tuned to EH_{11} and EH_{21} respectively.

15   Different designs of mode converter based on multimode waveguides are possible. Essentially, the mode converter design described herein is a multimode waveguide version of the Michelson interferometer. The interferometer serves the purpose of allowing the fundamental mode input field to be split into two components which are then given appropriate tilt magnitudes of opposite senses, before being recombined.

20   A multimode waveguide version of the Mach-Zehnder interferometer could provide a similar function. In the Michelson and Mach-Zehnder versions of the mode converter, improved mode purity can be achieved by increasing the waist size of the TEM_{00} input beam. The generated modes would be perfect if the input field was a plane wave. However, in the case of TEM_{00} input fields where the input beam waist, w, is

25   greater than 0.7a, the waveguide optical path length between the input plane and the fully reflecting tiltable mirrors must be an integer multiple of the length of multimode waveguide required to provide input field regeneration. This length of multimode waveguide is given as, $L = (2a)^2/\lambda$, for a hollow dielectric waveguide.

30   The most general implementation of the mode generation process is achieved by launching two plane wave beams of opposite tilts and with an appropriate phase offset between them into a multimode waveguide. The waveguide could be of zero length, i.e. an aperture. The tilted beams may be produced by acousto-optic or electro-optic modulators. In these embodiments, the processes of scene illumination,

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mode generation and field analysis could be simplified if they were to be performed independently. In such embodiments, the output from a laser source could be split into major and minor components. The major component would be used to illuminate the scene whilst the minor component would act as the input to a mode generator.

5   The output from the mode generator would then be mixed with the field returned from the scene in a separate multimode interferometer such that the mode analysis could be performed.

Other ways of generating the required spectrum of mode for the mode tunable local

10   oscillator are also possible. For example the tunable mode converter 28 may be replaced by a waveguide laser with a square cross section providing controllable multimode output. Higher order modes can be generated by varying the way in which the gain medium is pumped, by tilting the resonator mirrors, by varying the cavity length and by placing a moveable grid of wires over the resonator mirrors. In this

15   configuration a separate laser source 24 operating on the fundamental quasi-Gaussian mode would be used to illuminate the scene. If the laser source 24 and the mode tunable laser are stabilized in order to prevent relative drift in their frequencies, they could be frequency offset with respect to one another in order to generate a know high frequency beat signal. The fact that the different laser modes of the mode

20   tunable laser will have different oscillation frequencies will also mean that the mode that the mode tunable laser is running on can be identified from the beat frequency. This could be used as a discriminant in order to lock the mode tunable laser to a given mode. For example, if the mode output of the laser changed as a function of the voltage applied to a piezoelectric cavity length controller, an electronic feedback

25   circuit could be designed to keep the cavity length at a value that produced a given beat frequency and hence a given transverse mode.

The concept has been described in the context of mixing the modes generated by the mode generator/converter together with the field to be analyzed in a multimode

30   waveguide structure and then detecting the resultant field on a detector placed at the exit of the multimode waveguide. The mixing process need not be undertaken in a multimode waveguide. Mixing could be arranged to occur on a multidielectric etalon mounted in free space with the resultant field detected on the face of a detector mounted in free space. In order for this embodiment to operate correctly the modes

generated in the mode converter/generator would need to be accurately imaged onto the detector. In order to understand this embodiment it is useful to think of the detector as a multimode waveguide of zero length.

5   The embodiments described so far have only considered field analysis in the context of the orthogonal modes of square sectioned waveguides. Analysis could be undertaken with the more general class of modes of rectangular sectioned waveguides or the Bessel modes of circular cross sectioned waveguides. Any waveguide which supports a power orthogonal set of modes could be used as the
10   basis of an analyzer.

The embodiments described so far have only considered field analysis in the context of power orthogonal waveguide modes. Analysis can be undertaken in terms of any set of power orthogonal optical field functions which can be generated. These could
15   be the Hermite-Gaussian modes defined in relation to a rectangular coordinate free space system, or the Laguerre-Gaussian modes of a cylindrical coordinate free space system. In these implementations the lateral extent of the modes varies with their order. The higher the order of the mode the larger its width. In this case the detector would need to be large enough to capture the highest order mode that was required
20   for the analysis. This differs from the waveguide mode implementations were the lateral extent of all modes is defined by the waveguide cross section.

The embodiments described so far have only considered field analysis where the analysis process is undertaken in a multimode waveguide or free space version of
25   the widely used Michelson interferometer. Other forms of interferometer can be used to perform the field analysis process, including both multimode waveguide and free space versions of the Mach-Zehnder interferometer. The use of Mach-Zehnder type interferometers solely based on multimode waveguides is also possible. Here, a suitably design multimode waveguide takes the place of the etalon in the embodiment
30   described herein. The resulting all-waveguide interferometer has two multimode input waveguides to carry: (i) the field to be analyzed, and, (ii) the output from the mode converter/generator. These input guides feed into another wider multimode waveguide section which provides the mixing function. The resultant fields of the mixing process are carried out in two multimode output guides. A detector placed at

the exit of one would be used to make the beat measurements. The all-waveguide form of interferometer could also be used as the basis of a mode generator/converter. In integrated optic implementations of the all-waveguide mode generator/converter electro-optic phase modulators or SAW devices could be used to

5 generate the linear phase shifts produced by the tilted mirrors in the embodiment described in detail herein. Such modulators could also be used to provide a frequency offset between the output from the mode converter and the scene field to be analyzed.

10 The analyzer 10 may be incorporated in an array of like analyzers. The array may be arranged to receive reflected radiation from a scene. Each individual analyzer such as 10 may be arranged to generate a set of modes in its mode converter such as 28. For example, the analyzer 10 may be arranged to detect modes EH_{11} to EH_{10}, whereas a second analyzer may be arranged to detect modes EH_{21} to $EH_{2,10}$ etc.

15 This enables more rapid analysis of modes reflected from a scene. Such an application may be particularly useful for surveillance work, where the nature of a scene must be analyzed rapidly.

An array of analyzers in which each was arranged to detect a full spectrum of modes,

20 could also act as an alternative form of phased array receiver. In this arrangement, the field resolution at any sub-aperture, and hence the resolution of the complete array, would be significantly better than that achievable with a conventional phased receiver array based on the sole use of fundamental mode local oscillators at each sub-aperture.

25

In the multimode waveguide embodiments of the concept described so far, the multimode waveguides have been hollow in nature and have cross sections of millimetres. In such waveguides there is an air core surrounded by a dielectric cladding. For 10.6 μm radiation from a CO_2 laser source, polycrystalline alumina is a

30 good cladding material in terms of creating low loss waveguides because of its appropriate complex refractive index properties (i.e. n<1 at 10.6 μm). When using such dielectric materials, the hollow multimode waveguide structure may be fabricated from a series of plates of the dielectric material. Alternatively, it may be formed from a block of the dielectric material, with the waveguides being etched or

machined into the block.

The multimode waveguides need not be hollow waveguides, they can be solid core waveguides with a solid cladding. In such waveguides the refractive index ratios between the core and cladding are arranged to as to allow the waveguide to support many modes. GaAs/AlGaAs waveguides can be designed to be multimode. The waveguide structures are etched into a suitably designed epitaxial layer using ion beam assisted etching techniques. GaAs/AlGaAs waveguides of a few micrometers cross section can be designed to support many modes. In this context, it is interesting to note that, as the field resolution achieved with the analyzer concept described herein is dependent on the highest order mode that a measurement can be undertaken for, and not the lateral extent of the detector used to make the measurement; systems based on small dimension waveguides which support a good spectrum of higher order modes could provide very high resolution field analysis capabilities. Such analyzers could be useful for coherent microscopy, and could also be very useful for making field measurements at points in the electromagnetic spectrum where small dimension detector arrays are not available.

In the embodiments described so far the radiation has been 10.6 μm radiation from a CO_2 laser source. In principle with the right optical/waveguide technologies and laser/maser sources, the underlying concepts are applicable across the electromagnetic spectrum.

Implementation of the underlying concepts need not be solely based on the use of laser sources. Narrow linewidth quasi-coherent light sources can be used as an alternative to a laser. In this context light from distant astronomical objects can also be analyzed in a suitable implementation of the analyzer. In such an implementation there would be two receiver apertures. The received light from one would be modally filtered in order to provide a fundamental mode input for the mode converter. The output from the mode converter would be mixed with the field received from the other aperture. As the fundamental mode content of the input to the mode converter would vary due to variations in the fundamental mode component of the received field, this would have to be monitored and used to apply a suitable correction to mode amplitude measurements.

In a further embodiment, an analyzer can be arranged to act as a transmitter. By suitable control of the relative mode amplitudes and phases at the outputs of the analyzer, a transmitted beam can be produced from a suitable sum of independently

5 generated EH_{mn} modes.

The underlying concepts herein described could also be used as the basis of a communications system wherein individual modes are modulated in phase, frequency, or amplitude before being multiplexed and transmitted through a

10 multimode propagation medium. The information carried on each mode could then be extracted by means of coherent mixing with the appropriate output of a mode generator.

CLAIMS

1.   A radiation field analyzer for analysing at least partially coherent radiation received from a scene wherein the analyzer includes combining means for combining the coherent radiation from the scene with each of a plurality of orthogonal spatial radiation mode fields to provide interference signals, and detecting means for detecting the interference signals and for providing an analysis of the radiation from the scene in the form of a spatial mode spectrum.

2.   A radiation field analyzer according to Claim 1 wherein the combining means comprises a multimode waveguide structure.

3.   A radiation field analyzer according to Claim 2 wherein the multimode waveguide structure comprises a plurality of waveguides formed from a dielectric material.

4.   A radiation field analyzer according to Claim 2 wherein the multimode waveguide structure is formed from a plurality of segments of a dielectric material.

5.   A radiation field analyzer according to Claim 3 or Claim 4 wherein the dielectric material is alumina.

6.   A radiation field analyzer according to any one of Claims 1 to 5 wherein the analyzer includes a plurality of combining means each for combining radiation from the scene with a set of spatial radiation mode fields.

7.   A radiation field analyzer according to Claim 6 wherein each of the combining means combines radiation from the scene with a set of spatial radiation mode fields different from those combined by the other combining means

8.   A radiation field analyzer according to Claim 6 or Claim 7 wherein the analyzer is arranged as a phased array receiver and includes a plurality of sub-apertures, each providing means for performing a spatial mode analysis.

9.   A radiation field analyzer according to any preceding claim wherein the analyzer includes converting means for generating the spatial radiation mode fields by converting radiation of at least one mode into radiation of differing modes.

10.   A radiation field analyzer according to Claim 9 wherein the converting means provides means for generating a set of spatial radiation mode fields from a fundamental mode input.

11.   A radiation field analyzer according to Claim 9 wherein the converting means incorporates at least one mirror arranged for rotation about two axes to generate a set of radiation mode fields.

12.   A radiation field analyzer according to Claim 11 wherein the analyzer incorporates at least two mirrors, each arranged for rotation about two axes.

13.   A radiation field analyzer according to Claim 12 wherein the mode converter includes means for selectively generating only one of symmetric and antisymmetric mode fields at any one particular time.

14.   A radiation field analyzer according to Claim 12 or Claim 13 wherein the converting means is arranged to generate a signal of substantially one radiation mode field at any one particular time.

15.   A radiation field analyzer according to Claim 1 wherein the analyzer includes a waveguide laser source for generating the spatial radiation mode fields.

16.   A radiation field analyzer according to Claim 15 wherein the waveguide laser source is frequency locked to a main laser source which is arranged to illuminate the scene.

17. A radiation field analyzer according to any one of Claims 1 to 16 wherein the analyzer includes a main laser source arranged to illuminate the scene through the combining means.

18. A radiation field analyzer according to Claims 17 wherein the main laser source is a CO_2 laser.

19. A radiation field analyzer according to any preceding claim wherein the combining means is arranged to generate the interference signals by phase modulating the spatial radiation mode fields with respect to the radiation received from the scene.

20. A radiation field analyzer according to any one of Claims 1 to 18 wherein the detecting means includes at least one detector of cadmium mercury telluride.

21. A radiation field analyzer according to Claim 3 wherein the waveguides are rectangular sectioned waveguides of side 2a x 2b.

22. A radiation field analyzer according to Claim 21 wherein the waveguides are square cross sectioned waveguides of side 2a.

23. A radiation field analyzer according to any preceding claim wherein the detecting means is arranged to generate the modal spectrum analysis by measurement of both relative modal amplitude and phase.

24. A radiation field analyzer according to any preceding claim characterised in that the detecting means includes computer controlled equipment to carry out the modal spectrum analysis.

25. A radiation field analyzer according to Claim 1 wherein the combining means is a dielectric beam splitter.

26.   A radiation field analyzer according to Claim 2 wherein the multimode waveguide structure comprises an arrangement of solid waveguides.

27.   A radiation field analyzer according to Claim 26 wherein the solid waveguides are of semiconductor material.

28.   A radiation field analyzer according to Claim 27 wherein the semiconductor material is of the GaAs-GaAlAs system.

29.   A radiation field analyzer according to Claim 1 or Claim 2 wherein the combining means is a multimode waveguide interference coupler.

30.   A radiation field analyzer according to Claim 9 wherein the converting means comprises means for launching two appropriately tilted and phase offset light beams into a single multimode waveguide.

31.   A radiation field analyzer substantially as described herein with reference to Figures 1 to 3.

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Relevant Technical fields

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(ii) Int Cl (Edition   6)   G01S 7/48, 7/487, 7/493
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Databases (see over)

(i) UK Patent Office

(ii)

Online: WPI, CLAIMS, INSPEC

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Documents considered relevant following a search in respect of claims
1-31

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
	NONE	

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